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Bibi Nabilah Hassen [a,*], Dinesh Surroop [a], Jean Philippe Praene [b]

[a] Department of Chemical & Environmental Engineering, University of Mauritius, Mauritius
[b] PIMENT Laboratory, Department of Building Sciences and Environment, University of La Réunion, France

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ABSTRACT

This study examines the underlying concerns of global warming in the context of a small island developing states and the ensuing action of phasing out coal to keep global temperature rise below 1.5 °C, as stipulated by the Paris Agreement. Coal is amongst the most carbon intensive fuel, therefore transitioning to low-carbon fuels and renewables is necessary to decarbonise the energy system. In this study, a linear least-cost approach is applied to investigate the potential energy mix necessary to replace coal in Mauritius, using the Open-Source Energy Modelling System (OSeMOSYS). The research was initiated following the updated NDC submitted in 2021. The model spans from 2015 to 2040. This study demonstrates the need for even bolder renewable energy investments, like those in solar, wind, waste-to-energy, and biomass technologies, which would cost over 2.5 billion USD to develop but would reduce emissions by over 70% by 2040 and lessen the need for imported fossil fuels and hence decarbonise the electricity system.

1. Introduction

1.1. Overview

The COVID-19 pandemic has abruptly overturned the global supply chain and annihilated the world economy since its first appearance in 2019 [1,2]. With restrictions in international travel, trade and coordination, small island developing states (SIDS) including Mauritius have not been spared from the negative impacts of the gross domestic product (GDP). In 2022, while most nations are in economic recovery amidst another COVID-19 variant pandemic, the conflicts between Russia and Ukraine are threatening yet another blow to the economy of countries reliant on fuel importation [3]. With the share of petroleum and gas from Russia accounting for 12% and 17% of the global fuel production respectively [4], it is clear that redistribution of fossil fuels across the countries previously relying on Russia will have some economic impacts on Mauritius and other SIDS and may even affect energy security of a country. In 2020, fossil fuels for both electricity production and transport sector was around 86.7% in Mauritius which showed a high dependency on imported fossil fuel [5].

In addition to the climate change mitigation plans to restrict global temperature rise below 1.5 °C above pre-industrial levels, it is urgent that the country reduce its dependency on imported coal for electricity production [6,7]. To achieve the 40% reduction in emission as stipulated in the updated Nationally Determined Contribution (NDC) 2021, electricity production from coal needs to be drastically reduced and renewable energy integration needs to be accelerated in Mauritius [8]. Most research in literature on decarbonisation of energy systems are focussed on the phasing out of coal [9–11]. Coal is considered as the most carbon intensive fuel that is not only contributing tremendously to the global warming effect, but is causing numerous adverse environmental and health effects during the coal mining process [12]. Consequently, at the 26th Conference of Parties (COP26), an agreement was endorsed to phase out the use of coal for electricity production [13]. According to the insights from the IPCC Report on 1.5 °C, to be in line with the objectives of the Paris Agreement, the global coal usage must decrease by 80% by 2030, coal power plants must be discontinued by 2040 and OECD countries must end the utilisation of coal by 2030 [14,15].

In 2021, the percentage of emissions from coal represented 71.9% of the total emissions [16]. To displace the emissions produced from coal, considerable investments must be made in renewable energy technologies and low-carbon technologies. Transition from polluting fossil fuel to renewable energies is important to decarbonise the energy sector and help avoid the negative impacts of climate change [17]. For centuries, fossil fuels have been powering human development and economic development [18]. However, burning fossil fuels have released millions of tons of carbon dioxide into the atmosphere, the consequences of

* Corresponding author.
E-mail address: bibi.hassen2@umail.uom.ac.mu (B.N. Hassen).

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which proving to have detrimental impacts on human survival on earth. The increasing energy demand is fuelling the global energy related carbon dioxide (CO_2) emissions which is mostly due to a strong reliance on fossil fuels. To stay within the mandated temperature rise limit of 1.5 °C and mitigate climate change, there is an urgent need of a structural reform to energy sector to transition from fossil fuels to low-carbon and renewable sources of energy.

Energy transition to renewable energy presents a beneficial option for reducing fuel importation, hence offering immediate monetary opportunities and more autonomy through valorisation of local resources [19]. Additionally, in the context of SIDS and emerging countries, it is expected that the energy demand would increase with economic growth, therefore renewable energy could play a prominent role in climate actions and sustainability [20]. Furthermore, the current economic recovery following the COVID-19 pandemic, coupled with the economic damage from the ongoing confrontations between two countries have contributed a considerable slowing down in the world economic growth [21]. In Mauritius, the effects of this economic crisis and the strain on energy costs have already caused prices of commodities to skyrocket. The built-in inflation response to adapt to increased prices has weakened the poor and middle-class families even further. Increasing the amount renewable energy shares in the energy mix, in the long term may provide a solution to lower the cost of electricity and make the island more self-sufficient in terms of fuel importation [22,23].

1.2. Overview of Mauritius electricity grid system

Mauritius is an island nation classified under the category of Small Island Developing States (SIDS). Situated approximately 1132 km from the eastern coast of Madagascar, Mauritius is a volcanic island of about 1.3 million inhabitants [24,25]. After the independence of Mauritius from the British Colony, the island has transitioned from a low-income economy based on the sugar industry to an upper middle-income economy [25] centred on diverse sectors, such as tourism, manufacturing exports, agriculture, telecommunications and financial services. In reminiscence to all SIDS, Mauritius has similar substantial dependency on fossil fuels importations. In 2020, 86.7% of the total primary energy requirements were sourced from imported fossil fuels [5]. The costs of importation of petroleum fuels and coal in 2020 stood at an aggregated expenditure of 555.88 million USD, constituting 14.5% of the total imports expenses [5].

The existing electricity grid system in Mauritius consists of 498.47 MW of thermal power plants using fuel oil and kerosene Jet-A fuel, 32.5 MW of thermal power plants using only coal as fuel and 197.9 MW installed capacity operating on bagasse and coal during crop season and intercrop [26]. The renewable energy installed capacity, excluding bagasse, constitute of 60.44 MW of hydropower plants, 72.49 MW of solar farms, 9.35 MW of wind power, 3.3 MW of waste-to-energy plant using landfill gas, and 12.5 MW of photovoltaic small and medium scale distributed generation (SSDG/MSDG) [26]. The percentage of renewable energy generation in the energy mix of Mauritius stood at 23.9% in 2020, and 21.7% in 2019 [5].

In this paper, the different local renewable energy resources to support the energy transition from a fossil fuel centric energy system towards an energy system with more diversified renewable energy mix was analysed. Whilst the carbon-intensive nature and detrimental effects of using coal as fuel for energy generation has been well documented, and the importance of energy transition have been set up to enable climate resilience and adhere to the Sustainable Development Goals (SDGs). The aim of this paper is to provide policy insights to support the goal of the authorities to phase out the use of coal for electricity production by the year 2030. The Open-Source Energy Modelling System tool was therefore used to model the electricity generation system of the island of Mauritius. The scope of this study is limited to the analysis of the power generating technologies and the modelled period spans from 2015 to 2040, where the models were validated using available data for the period of 2015–2020 within a fractional uncertainty of less than 15%.

2. Methodology

The use of the OSeMOSYS tool was inspired by the Energy Modelling Platform for Africa (EMP-A), where participants from the energy sector were given training on energy modelling [27]. The purpose of this study is to promote the visibility of the African SIDS through research and to reconsider the idea of energy modelling from a fresh angle using an open-source energy modelling tool and, to a large extent, open-source data. The use of open source data was privileged to meet the U4RIA goals as stipulated by Howells et al., 2021 [28]. This study presents scenarios in line with the recent developments made in the renewable energy targets.

2.1. OSeMOSYS

The Open-Source Energy Modelling System (OSeMOSYS) is an energy system optimisation tool that can be used for energy planning for different spans of modelling period [29–31]. OSeMOSYS is a linear optimisation model that aims to find the least cost scenarios to meet the specific targets [29–31]. OSeMOSYS can be used to calculate the electricity generation mix that best matches the grid demands throughout the modelling period, also in each seasonal and daily segments within which the energy demands are divided. The OSeMOSYS tool can be used for diverse sizes of energy systems and can be used for predictive scenarios (based on current technologies and existing policies) and for explorative scenarios (analysis of a variety of technological perspectives assuming perfect foresight). In addition to finding the least expensive energy mix, the model may be further refined by including constraints to replicate actual circumstances such as.

- **Limiting the electricity generation of a power plant technology based on availability of fuel:** For example, limiting kerosene gas turbine operation that could be used for flexible generation response.
- **Limiting new capacity investment of a power plant technology**: For example, limiting new investment in utility-scale hydropower projects as most sites have been exploited.
- **Defining power plant availability:** For example, preventing the penetration of variable energy technologies such as solar energy during the night, bagasse power plants during off-seasons, or power plants during maintenance.
- **Setting the emission thresholds:** To meet the desired emission curtailment, the total annual emission from the generation mix can be restricted to promote green, low-carbon and carbon neutral technologies.

2.2. Data collection

Research was conducted to extract salient information from secondary data sources such as organisational reports, published articles and reports. Table 1 provides an illustration of the different data sources used in this study.

Table 1
Data sources.

Data	Sources
Existing Installed Capacity of Power Plants Demand Load Curves Annual Generation from Power Plants	Central Electricity Board Annual Reports (2015–2020)
Capital and Operational Expenses	Renewable Energy Roadmap for the Island Nation of Mauritius (Author: Shea, 2017)
Energy Storage Costs	National Renewable Energy Laboratory (2021)

2.3. Energy system structure

2.3.1. Reference energy system

The reference energy system (RES) is a simplified graphical representation of the energy system under consideration. It represents the different fuel inputs, conversion technologies, transmission and distribution, and the final electricity demand. The RES can be built in compliance with current and predicted energy policies. Fig. 1 depicts the RES of the Mauritius model with the OSeMOSYS standard nomenclature.

2.3.2. Time representation

Electricity demand and the availability energy resources such as solar and wind vary with time, which gives rise to fluctuating load curves and power generation outputs throughout different time of the day, week, and year. Consequently, time representation of the contrasting times of the day and seasons must be modelled separately. In this study, 96 time slices were defined which represented 4 types of 24-h days, namely.

- Summer day 1 during the period of January to March
- Transition day during the period of April to June
- Winter day during the period of July to September
- Summer day 2 during the period of October to December

Consequently, each of the 96 time slices during a particular year represented approximately 1.04% of the year.

2.3.3. Key parameters

Parameters are numerical inputs that defines the performance and sensitivity of the energy model. The parameters can be varied to calibrate a model, as well as defining new scenarios for analysis.

- **Electricity demand**

Data for the electricity demand were extracted from the Central Electricity Board Annual Reports for the years 2015–2020 and electricity demand projection for the period of 2021–2040 was extrapolated linearly with an annual increase of 3% based on the trend of electricity demand for the period of 2015–2019.

- **Techno-economic parameters**

The different costs associated with the power plant technologies and the technology performance parameters are important considerations that define the overall performance of the energy model optimisation given that OSeMOSYS aims at finding the least cost energy mix to sustain the demand.

The cost of fuel importation (variable costs of fuel imports) includes the purchasing cost, the insurance and freight price. The average costs of fuel imports were calculated using data for the years 2011–2020 from the Statistics Mauritius Energy Report.

- **Input activity ratio**

The input activity ratio refers to the rate of utilisation of a fuel by a technology as a ratio of the rate of activity and is calculated as follows:

$$Input\ Activity\ Ratio = \frac{1}{Efficiency\ of\ plant}$$

Table 2 shows the plant efficiency assumed in the model, and the evolution of efficiency of the transmissions and distribution network over time. Detailed generation data about the specific power plants can be obtained from the Central Electricity Board Publications.

2.3.4. Scenario selection and assumptions

- **Business as usual scenario**

The business-*as*-usual (BAU) scenario provides a representation of the existing technologies in use in Mauritius. In this scenario, it was assumed that there would be no changes in technology, no change in techno-economic conditions, and the share of renewable energy technologies would not evolve with time. Consequently, there was no capacity investment in hydro, solar, wind and bagasse technologies.

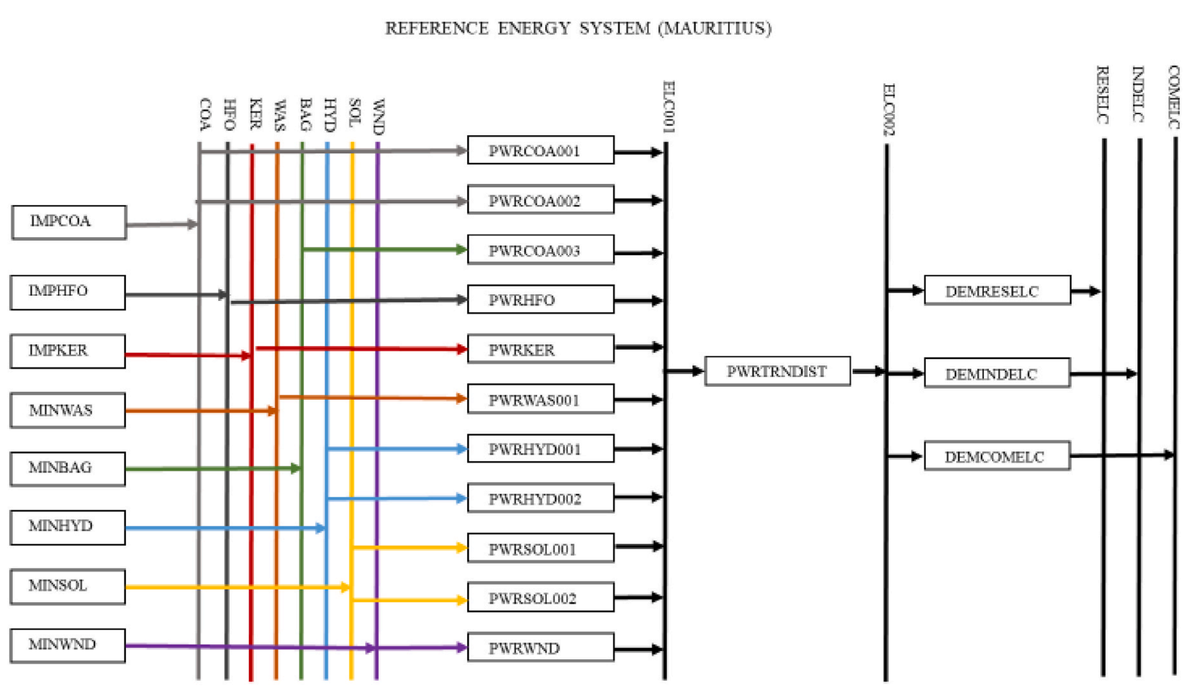

Fig. 1. Reference energy system for Mauritius.

Table 2
Plant efficiency and input activity ratio.

Technologies	Plant ID	Input Fuel	Efficiency		Input Activity Ratio
Coal Power Plant	PWRCOA001	Coal	0.35		2.857
Coal Cogeneration Plant	PWRCOA002	Coal	0.35		2.857
Bagasse Power Plant	PWRCOA003	Bagasse	0.35		2.857
Heavy Fuel Oil Power Plant	PWRHFO	Heavy Fuel Oil	0.35		2.857
Kerosene Gas Turbine	PWRKER	Kerosene Jet-A Fuel	0.3		3.333
Biomass Power Plant	PWRBIO001	Forest Biomass	0.35		2.857
Waste to Energy Plant	PWRWAS002	Refused Derived Fuel	0.35		2.857
Transmission and Distribution	PWRTRNDST	Electricity from Power Plant	Year	Efficiency	1.0705
			2015	93.41	
			2016	93.73	1.0669
			2017	93.55	1.0689
			2018	94.18	1.0618
			2019–2040	93.27	1.0722

Additionally, the annual activity of bagasse power plant was constrained to a maximum generation of 400 GWh due to the decreasing resource availability.

- **Scenario 1: Fossil Future**

Fossil future investigates what would be the likely future once coal power plants are removed from the grid in 2030 whilst keeping the renewable energy shares as in the status quo. Scenario 1 is an illustrative scenario whereby the consequence of delayed actualisation of long-term clean energy planning were investigated.

- **Scenario 2: Solar and Wind**

In scenario 2, the availability factor of coal power plants and cogeneration power plants using coal as fuel were set to zero as from year 2031 to achieve the coal phase out effect. This scenario investigates the potential of exponentially ramping up rooftop solar photovoltaic panels and solar photovoltaic farms, and wind farm to achieve the updated NDC goals of 40% renewables by 2025 and 60% renewables by 2030 [8].

- **Scenario 3: Hybrid Solar and Wind**

In scenario 3, two new hybrid technologies were introduced in year 2026 to achieve an exponential increase in renewable energy share for the 2030 targets - solar farm with 6 h battery energy storage systems and wind farm with 6 h battery storage. The purpose of this scenario investigates how hybrid technologies could help to reduce the capacity investments of traditional solar photovoltaic shares as compared to scenario 2.

- **Scenario 4: RDF with Hybrid Solar and Wind**

In scenario 4, in addition to the hybrid technologies from scenario 3, a new waste to energy technology was added to the energy mix. A limit of 200 GWh was added to restrict the annual activity of this new power plant technology to restrict the GHG emissions from incineration of municipal solid wastes.

- **Scenario 5: Biomass including RDF with Hybrid Solar and Wind**

In scenario 5, the potential of utilizing forest biomass was investigated. This energy model is an explorative scenario, due to the use of forest biomass may be associated with diverging conflicting views and since forests in Mauritius are protected by legal bindings as reserves and or approximately 30 000 ha of forest cover have private ownership [32]. The annual activity of the new technology was limited to at the most 350 GWh per annum.

3. Results and discussion

3.1. Business as usual (BAU)

In the Business as Usual (BAU) scenario, the future technology use trends were based on no technology changes, no major change in economies and no future capacity investments in renewable energy technologies. The increasing demand arising from economic growth, increase in the quality of living would be met by technologies as in the normal circumstances of the status quo. In the BAU scenario, the capacity investment in fossil fuel technologies were permitted to allow the model to optimise the least cost model to meet the growing energy demand. However, in the case of bagasse, the model was constraint to prevent capacity investment in bagasse technologies. Bagasse constraint was added to reflect the decreasing interest of sugar cane plantation around the island. According to the statistics, the production of sugar cane decreased from 3.4 million tonnes in 2019 to 2.6 million tonnes in 2020, which refers to a decline of 23% [33]. The drop in electricity demand in 2020 and 2021 demonstrates the reduction in demand owing to the fact that economic activities were significantly affected by the COVID-19 lockdown.

During the modelled period in Fig. 2, the electricity demand grew from 2472 GWh in 2015 to 4207 GWh in 2040. To cater for the growing demand, an investment of 62 MW was made in coal technologies in year 2023 and an additional 18 MW in year 2025. By the end of the modelling period, it was noted that the coal power plant installed capacity increased from 32.5 MW in 2022 to 220 MW in 2040. Additionally, whilst the model has exploited all available installed capacity to meet the demand, the electricity output from heavy fuel oil power plants increased by 13.7% in 2025 and 55.1% by 2040, respective to the base year 2015. The objective value which is indicative of the net present costs associated with this energy optimisation to satisfy the energy demand from 2015 to 2040 was estimated at 2.0443 billion USD.

3.2. Scenario 1: fossil future

In accordance with the global agreement during the 26th Conference of Parties (COP26) held in Glasgow, where 190 countries and organisation agreed to phase out coal, as coal is considered as the most carbon intensive fuel [34]. In the updated Nationally Determined Contribution Report submitted in October 2021, it is forecasted to phase out coal by year 2030. In this view, this scenario investigates the potential of delayed response or the persistent of oil utilisation due to its economic efficiency, reliability and energy content.

As observe in Fig. 3, it can be observed that this scenario entails the progressive phase out of coal power plants. The installed capacity of power plants using only coal as fuel decreased from 60.9 MW to 32.5 MW in 2019 due to the closing down of the CEL (Beau Champ) Coal Power Plant. The last remaining coal-only power plant of 32.5 MW was

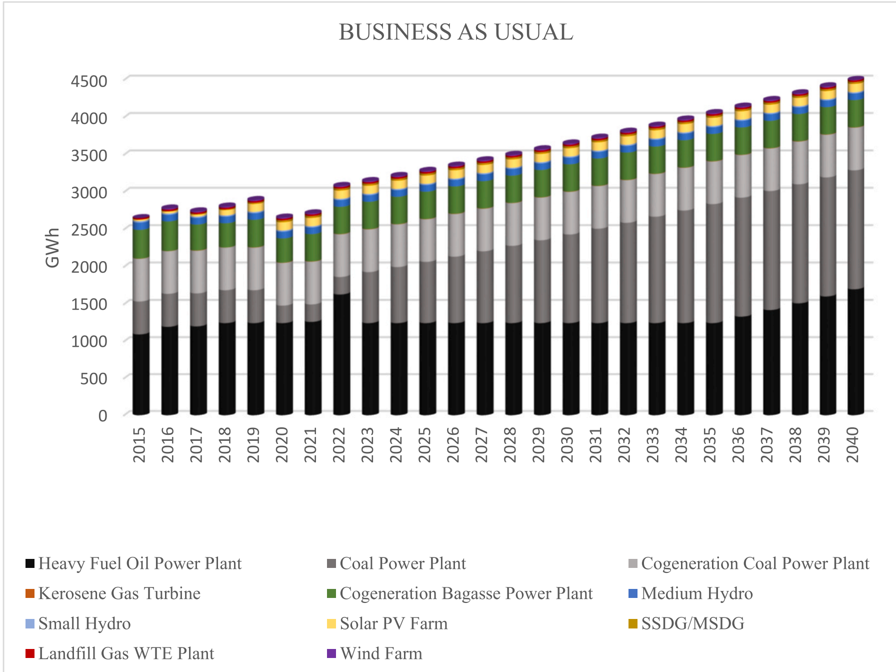

Fig. 2. Business as usual scenario annual electricity generation.

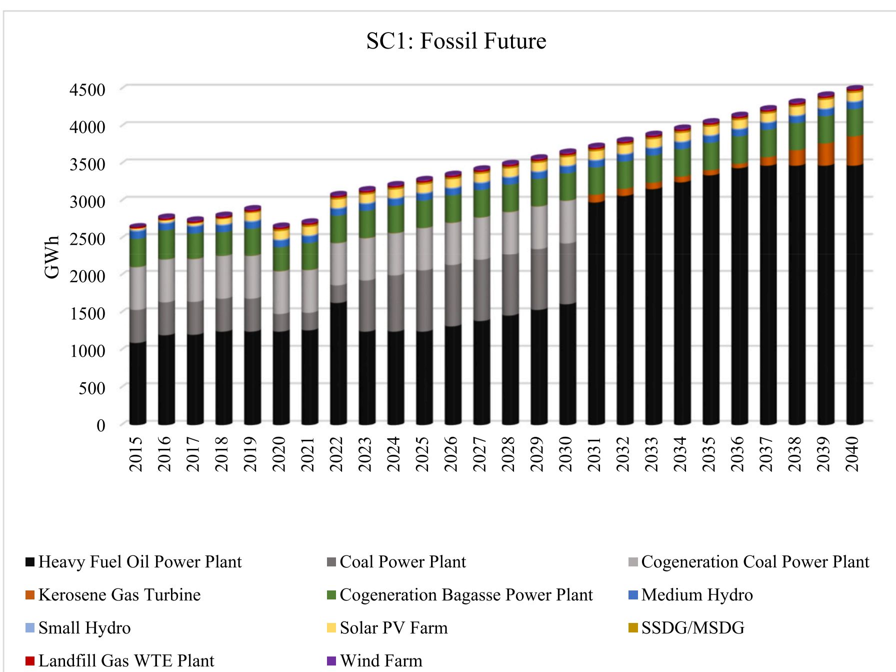

Fig. 3. Scenario 1 annual electricity generation.

removed from the generating mix in year 2030. Additionally, the cogeneration plants using coal during intercrop season were also forecasted to cease activity in the year 2030. In this scenario, the shares of solar energy and wind energy were presumed to increase by minute amounts in response to delayed deployment of battery energy storage systems. Consequently, as it can be observed in Fig. 3, a large majority of the energy generation were compensated by the heavy fuel oil (HFO) power plants. Over the modelled period from 2015 to 2040, there was a net capacity investment of 148.5 MW in HFO power plants which is expected to supply up to 82% of the electricity demand by year 2040.

There was a total of 80.8 MW installed capacity of coal power plant installed by 2025 to sustain the increasing electricity demand. Since this scenario focuses mainly of the utilisation of fossil fuels to cater for the growth in electricity consumption, the capacity investments in coal and HFO plants were permitted. Consequently, despite the fact that coal plants would cease activity in 2030, there were investments in coal, as coal is least costly for its energy potential compared than HFO. Therefore, despite the economic benefits, this 80.8 MW investment is not worth the effort as it will be intended to meet the needs for only 5 years, and it will not recover the investment. From 2031 and onwards, the existing 78.4 MW of Kerosene (Jet-A Fuel) powered gas turbines were further exploited to preserve energy security. The share of electricity produced from kerosene increased from 0.075% in 2015 to 2.75% in 2031 and almost 8.68% in 2040. The objective value for scenario 1 was optimised at 2.3089 billion USD.

3.3. Scenario 2: solar and wind

Scenario 2 in Fig. 4 investigates the utilisation of solar photovoltaic farms and wind farm to replace coal power plants and achieve the NDC renewable energy shares targets of 40% by 2025 and 60% by 2040. This scenario also models the mass deployment of rooftop solar photovoltaic panels use for residential and commercial activities, as well as illustrate the increasing investment in rooftop solar panels for charging electric vehicles in line with the new policies announced in the budget plan 2022–2023 to promote electric mobility [35]. In this scenario, despite the higher capacity factors of wind farms compared for solar farms, new capacity investments in wind were restricted to 150 MW. To achieve the 40% renewable energy shares by 2025, a total capacity investment of 390 MW of utility scale solar photovoltaic plants, 70 MW of rooftop solar PV (which corresponds to 7000 household assuming each install 10 kW) and 100 MW of wind would be required, which corresponds to a total cumulative capital investment of 764.115 million USD. Whilst achieving the 60% renewable energy share by 2030 would require additional capacity investments of 1250 MW utility scale solar PV, 250 MW rooftop solar PV and 50 MW of wind. The total capital investment expenditure for this second phase is expected to cost approximately 1.745 billion USD. The total discounted cost of this scenario was optimised at 3.6171 billion USD.

3.4. Scenario 3: hybrid solar and wind

The greatest ambiguity about solar and wind is that both renewable energy resources are variable. Consequently, electricity produced from solar, and wind alone cannot be used as a dispatchable technologies, that is, the power plants cannot be switched on and off to sustain the various fluctuating demand loads of the grid. To accommodate larger renewable energy shares on the grid, changes can be made to the grid to allow more flexibility. One of the most cost-effective solutions on the short term, is the use of hybrid technologies to compensate for fluctuations in output from variable renewable energy power plants [36,37]. Hybrid technologies refer to renewable energy plants that are balanced with a second type of generation technology or storage. In scenario 2, as illustrated in Fig. 5 it can be observed that a total investment of 1960 MW of solar plants would be required to achieve the NDC targets. This unreasonable quantity is attributable to the fact that solar plants without storage would operate approximately 8 to 11 h a day depending on the season and prevailing weather conditions. Consequently, more capacity investments would be required to achieve the renewable energy targets and sustain the growing demands. In addition to the massive financial investments, such investments would have an exorbitant land footprint. In this scenario, investments were made into two new hybrid technologies – solar farm with battery and wind farm with battery. The two new plants were included in the energy mix in 2026. Consequently, to accomplish the 60% renewable energy by 2030, 162.5 MW utility scale solar photovoltaic plants with battery storage and 190.1 MW wind farm with battery storage. By the end of the modelled year in 2040, a supplementary of 175.7 MW of rooftop solar PV and 57 MW of hybrid wind farm would have to be introduced to the mix. The objective value of the scenario 3 was optimised at 2.5374 billion USD.

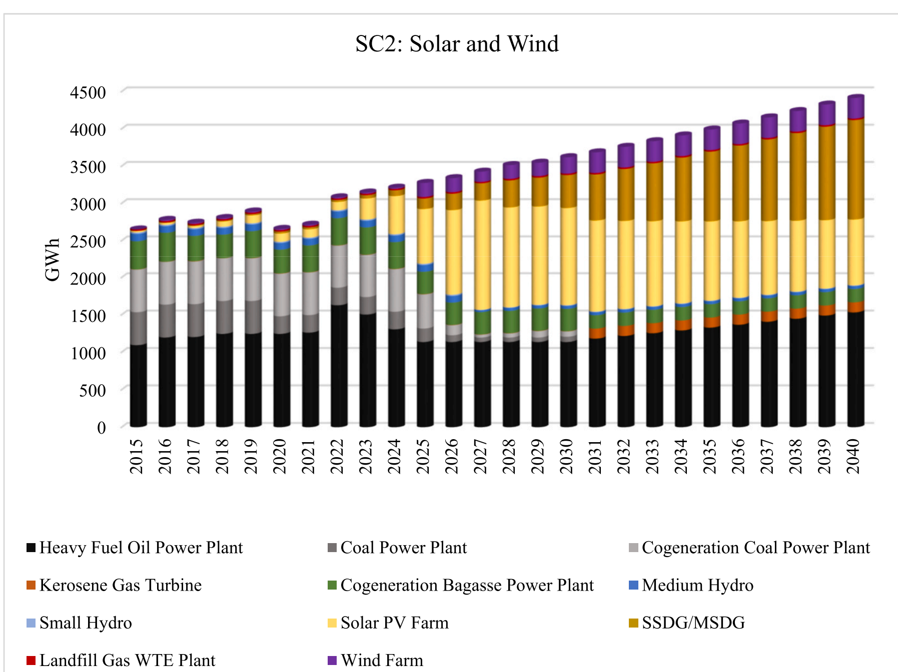

Fig. 4. Scenario 2 annual electricity generation.

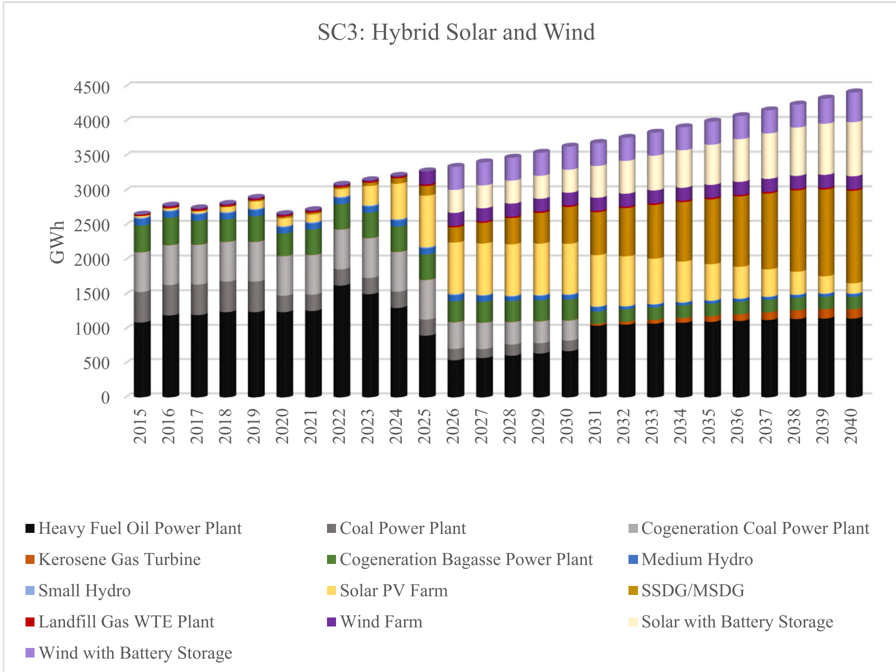

Fig. 5. Scenario 3 annual electricity generation.

3.5. Scenario 4: RDF with hybrid solar and wind

Small island developing states (SIDS) have a common problematic issue: most SIDS depends largely on imported fossil fuels mostly for transport and electricity production. This heavy reliance takes a heavy toll on the fragile island economy, further encumber the island with risk of supply disruptions and may affect energy security. While energy self-sufficiency may entail massive infrastructural and technological change, and would require investments in more installed capacity, exploiting local energy resources may help to alleviate the debt and improve energy resilience.

The disposal of solid waste has become a major challenge with the increasing tendency of the consumer society. The disposal of municipal solid wastes requires large land footprint, with tremendous environmental impacts on the surrounding areas around the landfill. Environmental impacts of landfills include contamination of surface water and subterranean water with leachates which may contain harmful substances such as heavy metals, and other contaminants [38]. In addition to air pollution caused by methane gas emanation and dusts, landfills have significant depreciate the value of properties and lands in its vicinity [38–40].

According to statistics, approximately 509 094 tonnes of solid waste

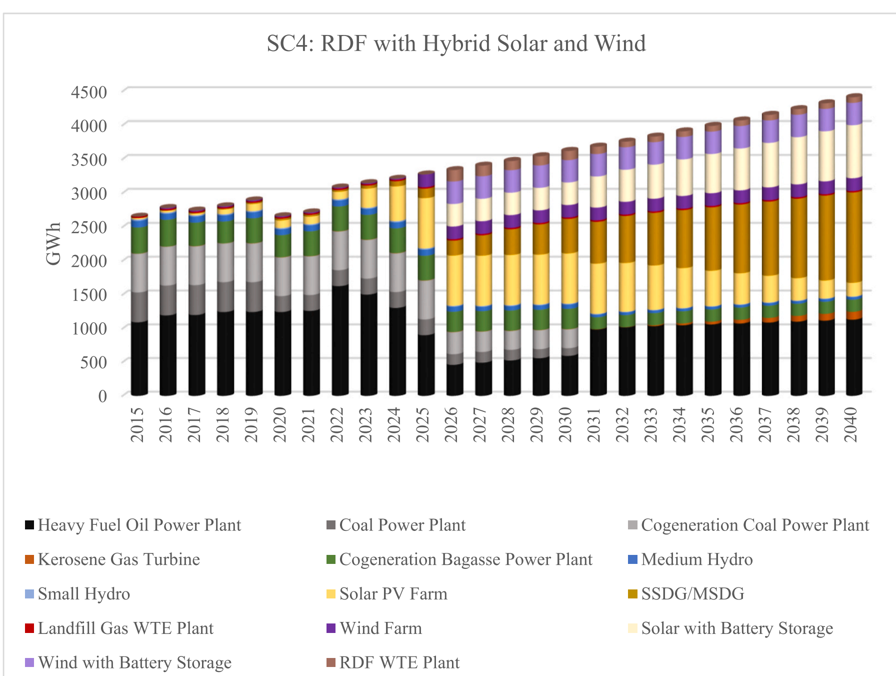

Fig. 6. Scenario 4 annual electricity generation.

were sent to the landfill in 2020 [41]. With increasing population and spread of the consumer society, it is very likely that solid waste generation in Mauritius exceeds the preliminary forecasts of 510 000 tonnes [42,43] of waste by 2034 as estimated by Bundhoo et al. (2016). Waste-to-energy conversion provides valorisation of an undesired energy resource and effective control for the set-up of a waste management system. At present, landfill gas is collected through a network of collection system within the landfill at Mare Chicose and fed to 3.3 MW turbine [5,26]. The current installation produce on average 22 GWh per annum and in 2020, production from the landfill gas increased to 25 GWh which indicates an increase of 25% compared to 2019 [5]. The energy potential in solid waste can be exploited through incineration technologies, gasification [44] and pyrolysis. In this scenario, the use of refused derived fuel (the combustible part of municipal solid waste) for incineration was investigated.

In this scenario in Fig. 6, in addition to the investments in hybrid solar and wind from scenario 3, a refused derived fuel waste-to-energy incineration power plant with an installed capacity of 30 MW was added to the energy mix in year 2016 to generate approximately 160 GWh of electricity on an annual basis. The net present cost for this scenario was estimated at 2.5821 billion USD.

3.6. Scenario 5: biomass including RDF with hybrid solar and wind

Biomass is considered as a useful sustainable resource for electricity generation because it is believed that the same amount carbon emissions released during the biomass combustion is captured during photosynthesis when new biomass are grown. The carbon-neutral nature of the biomass makes the usage of biomass an effective fuel to control emissions and mitigate climate change. Exploiting forest biomass for energy is a frequent practice in several countries such as Belgium, Denmark, The Netherlands, and United Kingdom [45]. Using forest biomass as fuel is considered as an optimistic solution because it reduces dependency on imported fuel, provides employment, reduces emissions and provides energy technology leadership. Energy technology leadership in this case refers to taking the lead to the usage and investment in innovative technologies that can be critical to the future of the country. Using biomass as an energy resource provides a dispatchable fuel resource that can be harness at any time of the day, hence providing a reliable source for baseload resources.

Unlike the conventional renewable energy resources, forest biomass is limited. Consequently, future increasing demands may not and should not be met by over-exploiting the natural forests. The objective of using forest biomass is mainly to alleviate dependency on imported fossil fuels and step closer towards self-sufficient energy resources. The total area of forest cover for Mauritius is approximately 47 159 ha (471.59 km^2) [32].

In addition to forest maintenance residues, there are several invasive woody plant species [46] that could potentially make exploiting forest biomass lucrative. These plants include.

- *Acacia nilotica*, also known as Gum Arabic tree, whose timber and seed pods could be utilised as an alternative source of renewable energy [47–49].
- *Eucalyptus robusta*, also known as the Swamp Mahogany tree. This wood species have an energy content of approximately 19 600–20 500 kJ/kg [50,51].
- *Livistona chinensis*, also known as the Chinese Fan Palm tree [52].
- *Ligustrum robustum* subsp. *Walkeri*, which is one of the most invasive plants in Mauritius, which is notorious for forest biodiversity [53].
- *Psidium cattleianum*, also known as the strawberry guava tree. Native of the Amazonian basin, this plant species was introduced in the 1700's and is considered as the 'worst' invasive species as the fruit seeds propagate over huge spans [54].
- *Ravenala madagascariensis*, also known as the traveller's palm tree. These species have a fast growth rate, which is ideal for biomass mining [55].

According to published research articles, production of forest biomass varies between 8 and 20 tonnes per hectare in moderate climate, while in tropical regions the yield is around 15–30 tonnes per hectare of forest [56].

Despite the reasonable yield as illustrated in Table 3 and Table 4, the ecological and practicability perception of the use of forest biomass can be controversial. The attitudes of communities towards the practice of cutting down trees for maintenance and energy biomass may often prompt conflicting opinions about the sustainability perception of the project [58]. Forests serve as terrestrial carbon sinks, implying that reduction of the forest area may be viewed as reducing the sequestration rate of carbon dioxide on the long term. Consequently, in this scenario it was assumed that the annual electricity production would not exceed 350 GWh.

Additionally, to prevent any additional investments in this new biomass power plant, the idle coal power plants and cogeneration power plants using coal and bagasse as fuel, were put to use during the 6 months off-crop season to harness electricity from forest biomass. According to energy model in Scenario 5, between 2026 and 2030, 135 MW of the existing coal facilities would be utilised for forest biomass to produce 300 GWh annually. After coal phase out in 2030, electricity produced from biomass could be increased to 350 GWh, 244 MW out of the existing 259.5 MW installed capacity of coal/coal-bagasse facilities would be reinstated to expand the biomass shares. The net present cost was optimised at 2.5838 billion USD (see Fig. 7).

3.7. Greenhouse gas emissions

In Fig. 8, it can be observed that the most noticeable conflicting difference in emission between the Business as usual (BAU) scenario and the Scenario 1, where the annual emissions increased by almost 12.03% in 2031 after the phasing out of coal in year 2030. This can be explained by the fact that Scenario 1 investigates the strong persistence of existing

Table 3
Available Forest biomass in Mauritius with reference to published facts in [56].

Scenario	Available Forest Biomass (Tonnes) (Assuming 47 159 Hectares of forest available)
Worst Case Scenario (8 Tonnes Per Hectare)	377 272
Best Case Scenario (30 Tonnes Per Hectare)	1 414 770

Table 4
Typical biomass energy potential from forest biomass (Data Source: [57]).

Fuel	Thermal Energy Yield (Combustion) GWh/Tonne	Electricity Yield GWh/Tonne	Bioenergy Potential [GWh/year]	
			Worst Case Scenario	Best Case Scenario
Fresh Wood (50–60% moisture content)	0.002	0.0006	226.4	848.9
Oven Dried Wood (25–35% moisture content)	0.0034	0.00102	384.8	1443.1
Wood Pellets (15–25% moisture content)	0.004	0.0012	452.7	1697.7

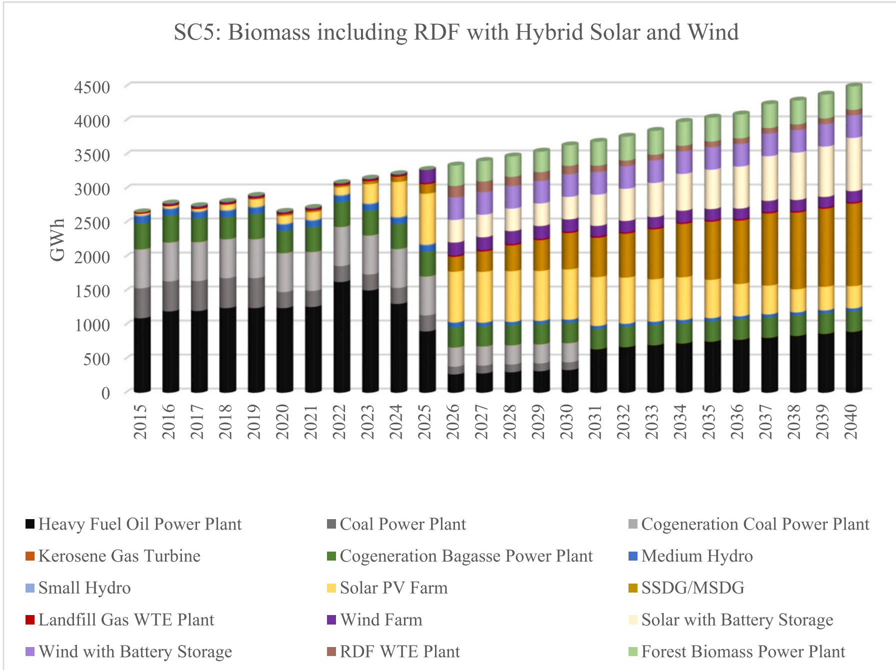

Fig. 7. Scenario 5 annual electricity generation.

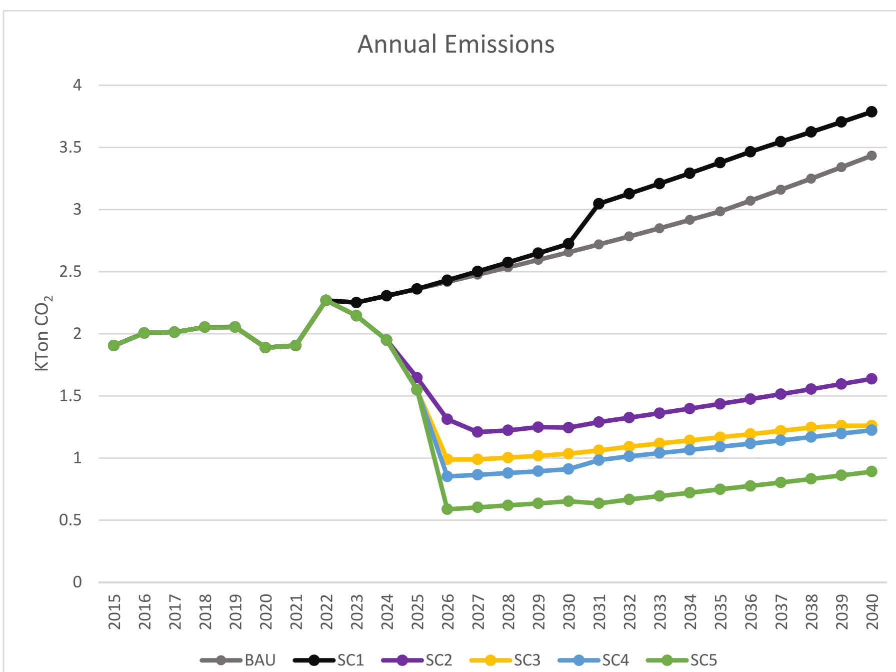

Fig. 8. Annual emissions by scenario.

fossil fuel technologies such as heavy fuel oil power plants and kerosene gas turbine. Compared to the business as usual, the generation from renewable energy technologies remained unchanged, whilst heavy fuel oil power plants and kerosene power plant stepped up to meet with the increasing demand. In Scenario 2, Scenario 3, Scenario 4 and Scenario 5, which have significantly higher investments renewable energy technologies from year 2023, demonstrate a substantially higher degree of decarbonisation effect as from year 2023. With the investments in solar farms, rooftop PV and wind farm in 2025, it is achievable to decarbonise the electricity production by 30.3% with scenario 2 and 34.4% with scenarios 3, 4 and 5. By 2030, with Scenario 2, Scenario 3, Scenario 4 and Scenario 5, the percentage of decarbonisation 53.2%, 61.1%, 65.7% and 75.4% correspondingly with respect to the business-*as*-usual scenario. With the addition of the RDF waste to energy plant in scenario 4, the decarbonisation effect is expected to increase by 1.05% by 2040 relative to Scenario 3 despite the GHG emissions generated from the incineration of municipal solid wastes. In scenario 5, with over 47.7% and 79.9% of generation accounted by renewable energy technologies (which includes variable solar, wind, as well as hybrid technologies and sustainable dispatchable technologies such as Waste-to-energy and biomass plants) respectively in 2025 and 2030, it is estimated that GHG emissions would be abated by 34.4% in 2025, 75.5% in 2030 and 74.1% in 2040 relative to the baseline year 2015.

3.8. *Investments*

Fig. 9 shows the aggregated investments for the different scenarios over the modelled period. In the business-*as*-usual scenario, it can be observed that investment is significantly less compared to the scenarios with higher percentage of renewables. This can be explained by the fact that an investment of 390.3 million USD to increase the installed capacity of coal power plants from 60.9 MW in 2015 to 220 MW in 2040, would have a superior electricity yield than renewable energy technologies because thermal power plants have better capacity factors. Similar trends were noted with scenario 1, which investigates a fossil future as human economic flourishing needs outweighs climatic needs. It was found that to sustain the growing energy demand, an investment of 489.1 million USD would be required to increase coal capacity from 60.9 MW to 113.3 MW and heavy fuel oil plants from 359.6 MW to 508.1 MW.

In Fig. 9, the most conspicuous remark is the significantly higher cumulative capital investments required to meet the demands with scenario 2. Due to the intermittent nature of solar and wind without battery energy storage system, significantly more capacities are needed to replace coal. To achieve the 40% renewable energy goal by 2025, 390 MW utility-scale solar, 70 MW solar distributed generation and 100 MW wind power, totalling 764.1 million USD would have to be invested. While the 60% renewable energy goal would require an additional 1745.7 million USD investment by 2030.

In scenario 1, a noticeable investment can be observed in year 2023, where 217 million USD were injected to increase the capacity of rooftop solar photovoltaic panels by 44.7 MW. Followed by an investment of 764 million USD over a span of 14 years to double the installed capacity of heavy fuel oil power plant.

In the scenarios 3, 4 and 5, there were substantial investments in the new innovative hybrid technologies from 2026 to 2040 – solar farm with battery and wind farm with battery as observed in Table 5.

In scenario 4, there was an investment of 127.11 million USD in a new waste-to-energy power plant to process refused derived fuel of installed capacity 30 MW. While in scenario 5, in addition to the new technologies added in the scenarios 2 and 3, it was forecasted that the new biomass power plant (operating off-crop season: 6 months a year) would require 244 MW of installed capacity to generate 350 GWh of electricity. However, no additional capital investments were associated with the biomass power plants, as it is expected the existing 259.5 MW of coal/coal-bagasse power plants would be able to be exploited.

4. Discussion of results

With the recent impacts of climate change, there has been a surge in interest in renewable energy projects as a means of mitigating global warming. The major goal of this research project is to examine paths to

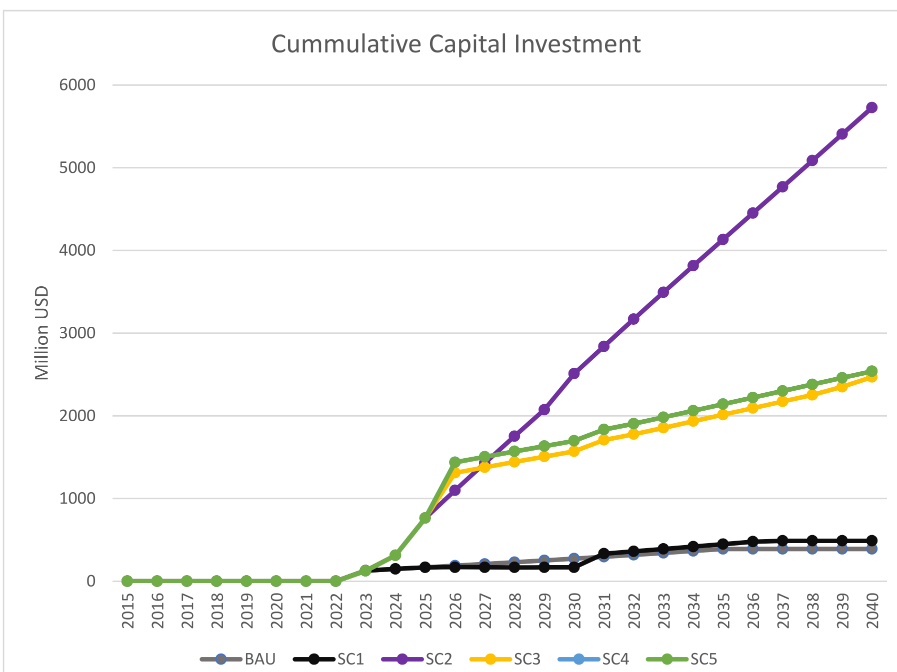

Fig. 9. Cumulative investment for the different scenarios.

Table 5
Overall investmen[1]t in renewable energy technologies.

Scenarios	Capacity Investment [MW]							Total Capital Investment [Million USD]
	Solar Farm	Rooftop Solar	Wind Farm	Solar -Battery	Wind-Battery	RDF	Biomass	
Scenario 2	4216.3	838.5	159.4	–	–	–	–	5481.1
Scenario 3	466.3	838.5	109.4	383.1	247.2	–	–	2469.3
Scenario 4	466.3	838.5	109.4	383.1	190.9	30	–	2538.6
Scenario 5	466.3	838.5	109.4	383.1	190.9	30	244	2[1]538.6

Table 6
Summary of renewable energy share and emissions reduction.

Scenarios	Renewable Energy Share	Percentage Emissions Abated in 2030 Relative to BAU
Scenario 1	17.70%	↑ 12.0%
Scenario 2	64.60%	↓ 53.2%
Scenario 3	69.00%	↓ 61.1%
Scenario 4	72.60%	↓ 65.7%
Scenario 5	79.90%	↓ 75.4%

decarbonise the energy systems of SIDS in order to keep global average temperature increases below 2 °C. Six scenarios were analysed: the business as usual, scenario 1 with a fossil fuel powered future, scenario 2 with solar and wind, scenario 3 with hybrid solar and wind, scenario 4 with addition of refused derived fuel waste to energy plant, and scenario 5 with the exploitation of local biomass. With climate policies backed with no actions, it is expected that the coal would dominate the energy mix. According to the business as usual model, it is predicted that output from coal power plants would increase by almost 110% between 2015 and 2040, which would increase the emissions level by 80.3% relative to the base year 2015.

Table 6 provides an overview of the renewable energy share in the energy mix for each scenario and the subsequent reduction in emissions relative to the business as usual for the year 2030.

In Scenario 1 where the possibility of using heavy fuel oil and kerosene to replace coal was investigated, it was found that a total capacity investment of 148.5 MW heavy fuel oil thermal power plant would be required to sustain the electricity demand by 2040. While the existing 78.4 MW gas turbine operating on kerosene currently used to peak demand, would have to be exploited over longer periods of time to preserve energy security. In 2022, Mauritius is currently standing 8 years from the phasing out of coal, rapid actions must be undertaken to shift towards cleaner and renewable energy technologies. Scenario 1 provides an illustration of the energy situation as fossil fuels maintain a stubborn grip on the economy of Mauritius.

In Scenario 2, investigated the potential of using solar and wind technologies to achieve 45% and 60% renewable energy targets by 2025 and 2030 respectively. To accomplish the 40% renewable energy share by 2025, a total capacity investment of 390 MW of grid scale solar photovoltaic plants, 70 MW of rooftop solar PV (roughly comparable to 7000 households installing 10 kW), and 100 MW of wind would be required, for a total cumulative investment capital of 764.115 million USD. To achieve the 60% renewable energy share by 2030, additional capacity investments of 1250 MW utility scale solar PV, 250 MW residential solar PV, and 50 MW wind are anticipated. With the gas station prices spiking post covid, the ongoing energy crisis caused by the Ukraine – Russia conflict, and financial incentives for electric vehicles, the switch from conventional internal combustion engine (ICE) vehicles to electric is becoming more affordable in Mauritius. Subsidies to install residential and corporate charging docks could be used as an effective incentive to promote electric vehicles over ICE vehicles.

Scenario 3 attempts to reduce the renewable technologies installed capacity suggested in scenario 2 through the addition of hybrid renewable technologies. In this case, funds were invested in two novel hybrid technologies: a solar farm with battery and a wind farm with battery. In 2026, the two additional units were added to the energy mix. As a result, to meet the 60% renewable energy target by 2030, 162.5 MW utility scale solar PV facilities with battery storage and 190.1 MW wind farm with battery storage will be expected. Unlike traditional renewable energy technologies, hybrid renewable energy systems would be beneficial in capturing energy otherwise lost during curtailment when yields from renewable are higher than the grid could support, for later use and to improve grid flexibility.

In Scenario 4, a waste to energy facility of installed capacity of 30 MW was added to the energy mix in year 2026. It was found that this new expansion in renewable energy technology would generate an additional 160 GWh of power each year. While in Scenario 5, the potential of using forest biomass was investigated. Between 2026 and 2030, 135 MW of current coal facilities could potentially be converted to forest biomass, producing 300 GWh per year. After coal is phased out in 2030, biomass power production may be expanded to 350 GWh, with 244 MW of the present 259.5 MW installed capacity of coal/coal-bagasse plants restored to enhance biomass proportions. Scenario 4 provides a solution by extracting valuable energy from wastes. Contrary to intermittent energy sources like solar and wind, waste-to-energy plants and forest biomass plants could potentially offer a reliable and efficient substitute for coal. This is because both of these technologies are dispatchable, meaning that the power plant could be configured on demand to accommodate the market needs and peak demands.

5. Conclusion

In consequence of the carbon intensive nature of coal, to achieve the specified goal of restricting the global temperature rise within 1.5 °C, there is the need to quickly terminate coal-based electricity production by 2030 and or 2040 at latest. In line with the Paris Agreement, Mauritius submitted an updated Nationally Determined Contribution documents in 2021, where Mauritius plans to phase out the usage of coal by 2030 [8]. Confronted with these circumstances, Mauritius would require enhancing its investments in research and technical innovations to replace coal.

Considering the prolongation of the status quo, it is expected that energy production from coal would double from 1028 GWh to 2163 GWh in 2040, with a net increase of coal installed capacity 187.7 MW by 2040. According to the business-*as*-usual scenario, it is expected that the annual carbon dioxide emissions would increase by 80.3% by the end of the modelling period. Mauritius is highly dependent on fossil fuels, thus, to improve the energy resilience of the island and sustain future energy demand, investments must be made towards deploying renewable energy technologies, expanding new capacities for sustainable dispatchable power plants. Some examples of sustainable dispatchable power plants includes waste-to-energy, landfill gas and biomass power plants that can be utilised to provide the base load. Hence, enabling the energy transition from fossil fuels to low-carbon and renewable technologies.

Scenario 5 extended the maximum extent of decarbonisation compared to the other scenarios, 34.4% relative to carbon dioxide emissions from the business-*as*-usual scenario. In scenario 4, there were investments of 244 MW in thermal power plant to process forest biomass, 30 MW of installed capacity in waste-to-energy (using refused derived fuel) incineration plant, 190.8 MW wind farm and 383.1 MW solar farm with a 6-h battery storage capacity. Nonetheless, there was a notable electricity output reduction from 1094 GWh (in 2015) to 894.7 GWh (in 2040), from the residual capacity of heavy fuel oil power plant that were exploited to balance and stabilise the grid.

[1] In scenario 5, there is no investment for the forest biomass plant as it is expected that the existing available coal/coal-bagasse power plants would be reinstated and utilised for biomass.

Strategic investments must be undertaken to securely replace coal and heavy fuel oil, energy security should remain the primary concern of the country, notwithstanding the urgency of climate change. The optimal option would entail investments in battery energy storage systems to accommodate more variable energy technologies and exploiting local resources such as biomass and solid waste.

The short-term policy priorities to support coal phase out by 2030 would necessitate investment in stabilising the grid to allow more variable renewable energy and specially to accommodate more grid connected distributed generation solar photovoltaic. Additionally, to address the intermittent nature of renewable energy, investments must be made in reliable dispatchable technologies such as hybrid renewable technologies, biomass and waste-to-energy plants.

Credit author statement

Nabilah B. Hassen: Conceptualisation, Data collection, Formal analysis, Writing – original draft, Writing – review & editing. Dinesh Surroop: Writing – review & editing. Jean-Philippe Praene: Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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